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A Design of Single Phase Induction Generator for Waterfall-hydro Turbine

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Abstract

This paper presents the design of the single phase induction generator for hydro turbine that driven by waterfall power. By the principle, when the water from the waterfall flows along the 1 inch pipe until to the nozzle, after that the nozzle directs water jet along a tangent to the circle through the center of the buckets. Finally, the buckets drive the rotor shaft of the single phase induction generator and generated 220V a.c. voltage for distributing electric load.

The design of single phase induction generator is modified by rewiring the winding of an old 1 HP, 220 V, 50 Hz motor from 4 poles to 6 poles. For impulse turbine design, this paper use the information model from Baan Kiriwong waterfall, Nakhorn Sri Thammarat province, south of Thailand for designing the dimension of the components of Pelton turbine with 9 ½ inches diameter and 18 buckets.

The result in laboratory test, at on-load test, the generator can distribute the load at 115.96W, 223V, 0.52A, 0.96P.F. - lagging with 1,200 rpm of shaft speed. For the applications test, the water pump are set the pressure as similar as the Baan Kiriwong waterfall and when the water jet against the bucket for moving the generator, at on-load test, the generator can distribute the load at 77.9W, 190V, 0.41A, 0.98P.F. - lagging with 1,100 rpm of shaft speed. It should be suitable for light load rural area and really far from electric distribution system.

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1. Introduction

Baan Kiriwong, Lanska district, Nakhorn Sri Thammarat Province, Southern of Thailand, a small village among of 4 Mountain (Yodpla Mountain, Hoi Sung Mountain, Ring Ro Mountain and Luang Mountain) that is the origin of headwaters and flow converges be 2 canals at the middle of village all year.

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This village is established more than 200 years ago and had the weather with the rainy season more than 6 months of the year, so the most of villagers earn a living with fruits gardeners such as Mangosteen, Rambutan, Long Kong, etc.

Because of all of the fruits garden area are on the mountain which high steep path and far to go, so the gardeners must be built the camp for temporarily staying, which they call Khanam, but unfortunately it no have power line come in Khanam because of its difficulty installation and high cost for investment. Beside that, the energy harvesting from solar energy couldn't be used all the year because of reason that the rainy season have more than 6 months of the year

However, fortunately at the top of mountains have a lot of waterfalls and flowing all the year. The gardeners could available been using this advantage to generate the electric energy from waterfall energy by modifying the motors on the market with many methods to be generator for many years ago as shown in fig. 1.

On during September 2009, the author had a chance to join a competition of a Thai television program that they called Kid Kham Mek program. The rule of this competition was thinking about how to build the hydro turbine generator for using in that area garden. With limited time and resources available in the neighborhood, finally when the competition was finished, something appeared to show the advantages and disadvantages between synchronous generator and induction generator.

The use of synchronous generator is shown in Fig. 2 (a), it will certainly produce ac. voltage even when the rotor is rotated at low speed. But there are problems such as a d.c. power supply for field circuit; the weight is too much to carry on into the deeper garden into the mountains; and so expensive. Meanwhile, the use of induction generator is shown in Fig. 2 (b), even if it complexes to connected the circuit but easier for maintenance, low cost and light weight for moving. However, one thing for consider design are the shaft speed of turbine. Due to the water from the waterfall, that flowing along the pipe until to the nozzle, might be varied pressure and also almost tendency to drive the shaft at low speed especially when generators are supplied the energy to loads, then the generator must be design to have many pole pairs. But mostly generators in the market only have 4 poles generator. So this paper will purpose the design method for single phase induction generator by using the information from Baan Kiriwong.



Fig. 1. Inventors of Kiriwong hydro turbines



Fig. 2. Generator comparison from Kid Kham Mek (a) Synchronous (b) Induction

Nomenclature

a.c.	Alternating current
d.c.	Direct current
p.f.	Power factor
V	Voltage: unit measurement of electric potential
A	Ampere: unit measurement of current
Hz	Herzt: unit measurement of frequency
HP	Horse power: unit mesurement of power
Nm	Newton-metre: unit measurement of torque
W	Watt: unit measurement of electric power
Wb	Weber: unit measurement of magnetic flux
min	Minute
sec	Second
m	Unit measurement of length in metre
mm.	Unit measurement of length in millimetre
mm ²	Unit measurement of cross sectional area in square millimetre
m ²	Unit measurement of cross sectional area in square metre
rpm	Speed measurement in revolutions per minute

2. Induction Generator [1]

Fig. 3. has shown the stator and rotor of induction machine. Stator part is installed by armature winding. Rotor part is installed by aluminium bars and short circuit at the end bars together.

Fig. 4. has shown the torque and speed characteristics of induction machine operation in 2 modes, First mode are normally in motor mode. When the armature winding is fed by a.c. voltage supply, then the stator flux will produce and induce the voltage in aluminium bar that effort to the rotor flux will produce at last. Finally, with the interaction between 2 fluxes, the motor can run up the speed to drive the load but notice that the motor couldn't run above the synchronous speed (N_{sync}) by itself because of induced voltage in aluminium bar can't be induced by the stator flux, when rotor speed is equal synchronous speed. However, if the shaft of the motor have any the powerful prime mover to drive the shaft that it turns over synchronous speed, the torque will move down to the negative plane and also the power will reversely flow back to the power supply. This status is called generator mode, or the second mode.

Unfortunately when the rotor part is driven by prime mover from standstill and the armature winding is connected to only load (no any external voltage supply) or stand alone operation, it doesn't have anything to induced voltage on armature winding because of rotor winding doesn't have any terminal to connect any power supply like the field winding of synchronous generator, or in the other hand, they couldn't produce the flux to flow across armature winding at stator part.

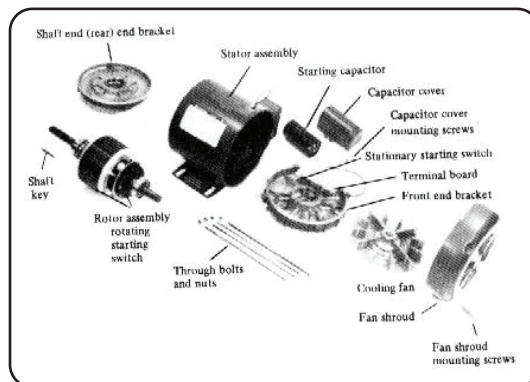


Fig. 3. Construction of Induction Generator

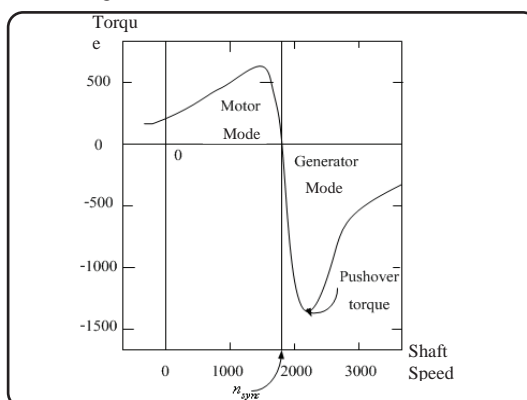


Fig. 4. Operation mode of Induction Machine

So the keyword for producing the voltage of induction generator has 2 keywords. The first keyword is the residual flux that it is collected within the core and also really small. The second keyword is the capacitor connection to the armature winding that it has shown in Fig. 5 (a). Due to the flux needs reactive power and the capacitor can supply the reactive power.

When the rotor shaft is driven by prime mover, the residual flux within rotor core is crossed to armature winding at stator part. So, the little induced voltage is induced in armature winding and also charged to the capacitor too. The little voltage in capacitor is built the new flux and it is added to the old residual flux that effort to the flux in the machine are increased, and also finally the voltage of induction generator is gradually increased as shown in Fig. 5 (b). Besides that the size of capacitance is effort to the building-up voltage of generator, especially if the capacitance is too small as shown in Fig. 5 (c).

Although the induction generator in the Fig. 5 (a) is three phases generator that uses three capacitors, but for single phase generator is just used only a capacitor that connected across the two wires of generator. In addition to the single phase induction machines in the market have almost two winding, such as split phase motor, capacitor motor, and the parameter of the two windings are not the same. So, it may be have the problem to the system from unequal voltage of two winding.

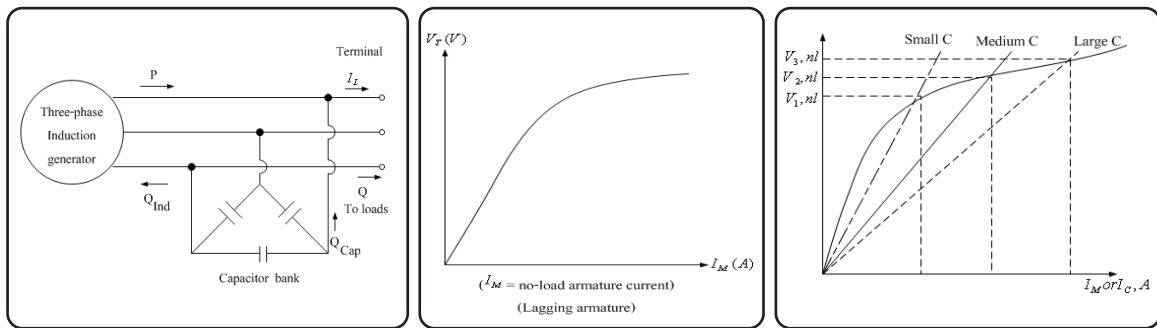


Fig. 5. Induction Generator in Stand Alone Operation (a) circuit (b) no-load characteristic (c) the effect of the magnitude of capacitor

3. Design concept of generator

This step is represented the design concept from the old 1 HP, 4 poles, 220V, 50Hz; capacitor run motor to be the new 6 poles induction generator which is following by these steps:

3.1. Coil span calculation

This section is determined number of coil span for armature winding.

$$f = \frac{NP}{120} \quad (1)$$

$$\text{Coil Group} = \frac{\text{Total Slot}}{\text{Pole} \times 2} \quad (2)$$

$$\gamma = \frac{360^\circ}{\text{Total Slot}} \times \frac{P}{2} \quad (3)$$

$$\text{Coil Span} = 1 + \frac{\text{Angle}}{\gamma} \quad (4)$$

When N is generator speed (rpm), f is generator frequency (Hz) and P is numbers of pole (poles), Coil Span is angle range of coil from count from first coil side to end coil side (unit measurement maybe use slot or degree), Coil group is number of sub coil that distributed in coil span of a big coil, Total Slot is total numbers of slot on stator core (slots), Pole or P is magnetic pole (poles), Phase is number of phase system, γ is slot angle in each slot, (electrical degree), Angle is the angles for installation coil at each slot.

Table 1 has shown the coil span calculation that following to step 1) and Fig. 6 has shown the concentrated winding diagram that suited for low speed machine.

Table 1. Parameters generator design in step 1

Name	Symbol	Design
Magnetic Pole	P	6 poles
Power	-	100W
Supply Voltage	-	220 V
Frequency	f	50 Hz
Phase	-	1 phase
Total Slot	-	24 slots
Slot angle	γ	45°
Coil Group	-	2
Coil Span of Outer Coil Group	-	Slot 1-6
Coil Span of Inner Coil Group	-	Slot 2-5

Table 2. Winding parameters for design in step 2

Name	Symbol	Design
Conversion Factor	-	1.67
Old outer and inner turn coil	N_{out}, N_{in}	32, 64 turns
New outer and inner turn coil	N_{out}, N_{in}	106, 53 turns
Circular Mil of Old Coil	CM_1	0.567 mm^2
Circular Mil of New Coil	CM_2	0.342 mm^2
No. of Copper Wire	No.	#24
Poles	P	36 poles
Flux per pole	ϕ	130,807 lines
Air Gap Density	B_g	$41,312 \text{ lines/mm}^2$
Tooth Density	B_{th}	$88,336 \text{ lines/mm}^2$

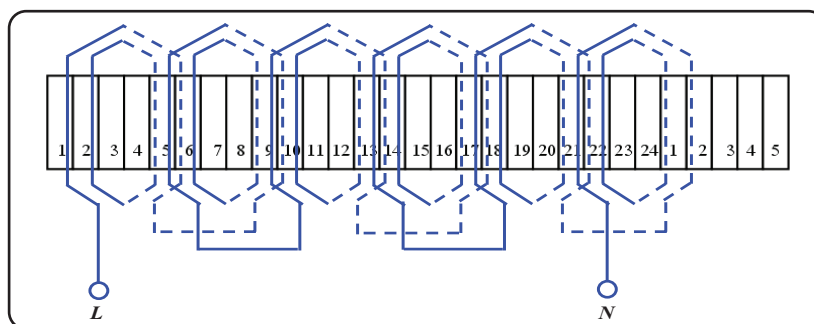


Fig. 6. Concentrated Winding Diagram

3.2. Wire size calculation [2]

This section is determined the new wire size for coil turn from step 3.1.

$$\text{Conversion factor} = \frac{V_2}{V_1} \times \sqrt{\frac{HP_1}{HP_2}} \times \sqrt{\frac{f_1}{f_2}} \times \sqrt{\frac{P_2}{P_1}} \quad (5)$$

$$CM_2 = CM_1 \times \frac{T_1}{T_2} \quad (6)$$

$$\text{Eff. Turn} = (T_1 \times CF_1) + (T_2 \times CF_2) + \dots \quad (7)$$

$$\phi = \frac{22,500,000 \times V \times \text{Phase}}{f \times \text{Eff. Turn} \times \text{Pole}} \quad (8)$$

$$B_{bi} = \frac{\phi}{2 \times l_c \times l_{bi} \times 0.95} \quad (9)$$

$$B_g = \frac{1.57 \times \phi \times \text{Pole}}{3.14 \times l_{bore} \times l_c} \quad (10)$$

$$B_{th} = \frac{1.57 \times \phi \times \text{Pole}}{l_c \times \text{Total Slot} \times l_{th} \times 0.95} \quad (11)$$

When V is voltage supply (V), HP is output power (hp), P is magnetic pole (poles), CM is circular mil area per turn of the winding, f is frequency (Hz), T is turn per coil of the winding, subscript 1, 2 are the old and new value, CF is chord factor of each coil, Eff. Turn is effective turn per pole, ϕ is flux per pole (lines), l_c is core length (mm.), l_{bi} is back iron length or the distance between frame and the bottom of slot (mm.), B_{bi} is back iron density (lines/mm.2), B_g is air gap density (lines/mm.2), l_{bore} is tooth length (mm.), l_{th} is tooth width (mm.). Fig. 7 has shown the dimensions of the stator slot variables. For the table 2 has shown the result parameters. Fig. 8 has shown the real installation of the armature winding at stator core.

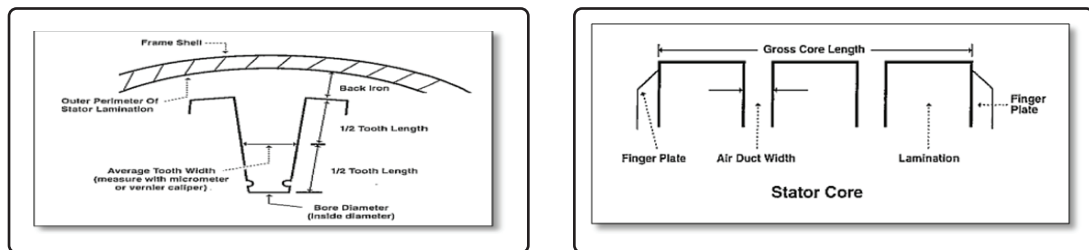


Fig. 7. The dimensions of Stator Slot

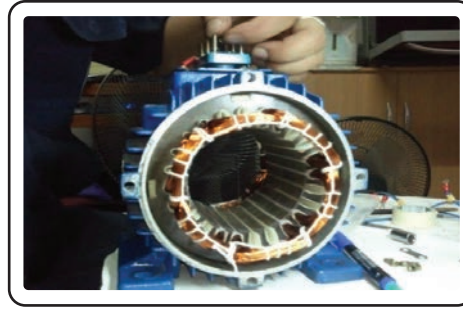


Fig. 8. Armature Winding at Stator Core

3.3. Turbine calculation [3]

This section is designed for turbine by using the information of the waterfall from Bann Kiriwong as the following:

- Diameter of pipe, D is 1 inch or 0.0254 m.
- Head height of the waterfall, H is 80 m.
- Flow rate, Q is 165 litres/minute

$$A_{pipe} = \pi D^2 / 4 \quad (12)$$

$$V_{pipe} = Q / A_{pipe} \quad (13)$$

$$V_{nozzle} = Q / A_{nozzle} \quad (14)$$

$$N = 862\sqrt{H} / D_i \quad (15)$$

$$S_1 = 2kD_i \quad (16)$$

$$B = \pi D_i \sin \beta / S_1 \quad (17)$$

$$P_{shaft} = 2\pi N T_{shaft} / 60 \quad (18)$$

$$T_{blade} = \rho V_{nozzle} A T_{shaft} (V_{nozzle} - U)(1 - \cos \beta) \quad (19)$$

When subscripts of pipe and nozzle are mean the value for pipe and nozzle, respectively, A is the cross sectional area, V is the velocity (m/Sec) Q is flow rate (litres/minute), D_i is diameter of disk (inches), N is turbine speed (rpm), P_{shaft} is shaft power (W), T_{shaft} is shaft torque (Nm), T_{blade} is the torque at turbine blade (Nm), ρ is water density (kg/m³), β is blade angle (degree), U is blade velocity (rpm)

Table 3 has shown the turbine calculation that following to step 3). Fig. 9 has shown the turbine blades.

Table 3. Parameters generator design in step 3

Name	Symbol	Design
Cross sectional area of pipe	A_{pipe}	$5.067 \times 10^{-4} \text{ m}^2$
Water velocity in the pipe	V_{pipe}	5.42 m/Sec
Cross sectional area of nozzle exit	A_{nozzle}	$0.786 \times 10^{-4} \text{ m}^2$
Water jet velocity out of nozzle	V_{nozzle}	35 m/Sec
Diameter of disk	D_i	12 cm.
Turbine Blade	B	18 Blades
Turbine speed	N	1,101 rpm



Fig. 9. Turbine Blades

4. Experimental

Generator testing could be divided in 2 parts as following:

4.1. Generator test

This test is operated in electrical machines laboratory and determined the characteristics of the prototype turbine generator as shown in Fig. 10.

In Fig. 11(a) has shown the no-load circuit for test terminal voltage and current waveform as shown in Fig. 11(b). Notice in the Fig. 11(b), the no-load current is quite high because it needs to produce the rotating flux across the air gap. For on-load test, the relationship of the voltage, current and power of generator with the speed have shown in Fig. 12.

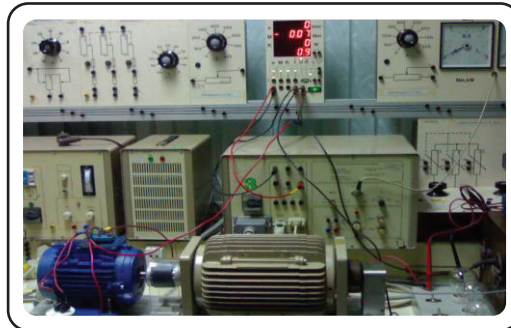


Fig. 10. Laboratory Test

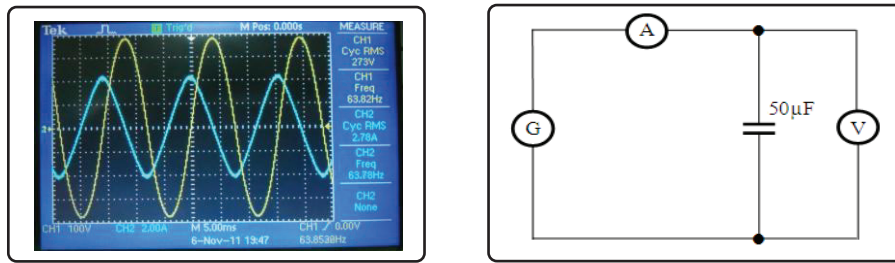


Fig. 11. No-load Test (a) No-load circuit (b) Waveform: CH1 = Terminal Voltage, CH2 = Generator Current

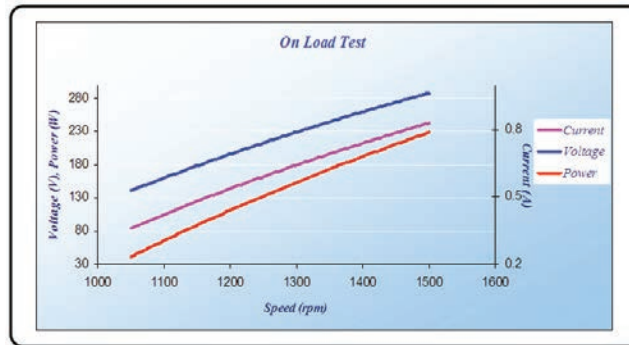


Fig. 12. On-load Test

Fig. 13 and 14 have shown the harmonics of voltage and current waveforms at no-load and on-load test. Notice that the 3rd harmonics of no-load current has a few magnitudes more than on-load current because of the capacitor supplies the reactive power that it effort to the shape of no-load current waveform is steep sinusoidal wave, when it compares with the voltage waveform. After the load current is increased, the 3rd harmonics has reduced because of the load draw the reactive power from capacitor and the on-load current is become to nearly sinusoidal waveform.

Table 4. Test Result

Load	Speed (Rpm)	Voltage (V)	Current (A)	Power (W)	Power factor
18 W Fluorescent	1100	224	0.08	17.92	0.99
50 W Electric Fan	1100	217	0.15	32.55	0.94
100 W Incandescent Lamp & 50W Electric Fan	1100	200	0.53	106	0.98
100 W Incandescent Lamp	1100	190	0.41	77.9	0.98

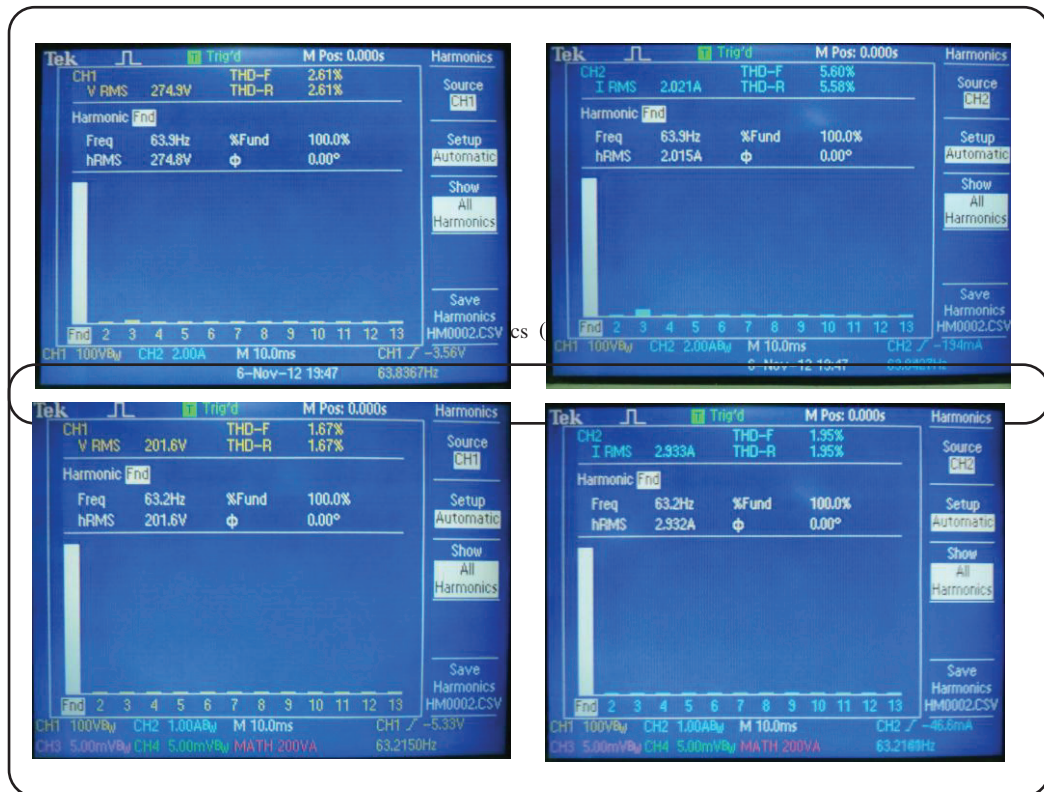


Fig. 14. On-load Harmonics (a) Voltage (b) Current

4.2. Applied test

This test has used the turbine to install at the shaft of the modified induction generator and used the water jet that set the pressure similar as the waterfall pressure, inject to turbine to driving the shaft as shown in Fig. 15.

When the induced voltage appears, the induced voltage has supplied to the loads and the table 4 has shown the results that the modified generator can supplied the light load in urban area and near waterfall.

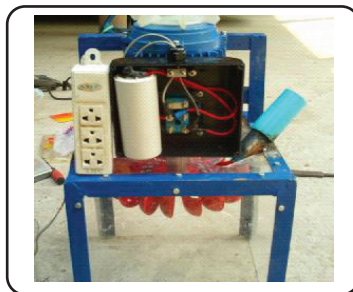


Fig. 15. Applied Test

5. Conclusion

Induced voltage from generator is directly proportional to the pressure of the water jet, which means the speed of shaft too. When the water jet is too low, induction generator may not be induced voltage. Beside that the change of the pressure of the water jet can be effect to the fluctuation of the voltage too. However, this problem can be fixed by using the converter to regulate the voltage all time.

The errors of prototype generator are come from calculation and especially stator construction because of no magnetization data of laminated sheet.

Acknowledgements

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